Journal of Arid Environments 154 (2018) 34–39

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Impacts of climate change and irrigation on lakes in arid northwest China

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ARTICLE INFO

Keywords:
Lake
Central Asia
Sustainability
Climate change
Irrigation
Water resource management

ABSTRACT

Lakes provide valuable water resources for people, life, and socioeconomic development in Northwestern China—a core region of the arid Central Asia where water is seriously deficient. In this study, we report the first investigation of the 30-year changes in all lakes larger than 1 km^2 in Northwestern China and the associated driving forces. We found that the number of lakes increased from 121 to 135, and the total lake area increased from 5495 km^2 to 6445 km^2 in this region. However, increases in lake area occurred mainly in the less populated mountainous areas caused by glacier melting and increase in precipitation. Conversely, lakes in the densely populated regions decreased by 40% since the year of 2000, which was significantly related to the increasing intensity of irrigation. These results not only suggest an ongoing water crisis in Northwest China but also reflect the lake dynamics in arid Central Asia where climate changes and irrigation are occurring prevalently with high intensity. Given the fact that the benefits of glacier melt in Central Asia can be substantially offset by intensive irrigation, we thus call an urgent need for a policy of sustainable water management in this critical region.

1. Introduction

Central Asia has one of the largest arid and semi-arid lands of the world, where lakes provide valuable surface water resource for local people, life, and socioeconomic development (Bai et al., 2011; Crootof et al., 2015). Quantifying the changes in its lakes and, especially, the factors underlying these changes, are therefore extremely important yet difficult, because of the complexity in geographical features (Lioubimtseva et al., 2005), political environments (Cowan, 2007), and climate changes (Lioubimtseva and Henebry, 2009; Zhao et al., 2011) in this critical region.

The arid Northwest China, with Xinjiang Uygur Autonomous Region as its core region (hereafter abbreviated as Xinjiang), is a typical dry-land experiencing lake changes during the past decades (Ma et al., 2010). The changes in lakes seen in Xinjiang is representative to the entire arid region of Central Asia. First, Xinjiang is a key part of Central Asia that borders with up to eight nations (Cowan, 2007). It spans over 1,665,000 square kilometers (about half the size of India) characterized by vast basins and deserts (Fig. 1). Water is seriously deficient in Xinjiang and lakes play an essential role in supplying valuable water resources for nearly 23 million local people (National Bureau of Statistics PRC, 2016). Secondly, changing climate (Lioubimtseva et al., 2005; Lioubimtseva and Henebry, 2009; Zhao et al., 2011), increasing human intervention (Micklin, 2007; Tao et al., 2015), and melting glaciers (Pritchard, 2017) are regarded as the main factors that control lake dynamics in Central Asia, and all of them are occurring simultaneously in Xinjiang with strong intensities. Specifically, the northern part of Xinjiang belongs to the Mongolian Plateau (Fig. 1) where climate change and human activities have caused severe negative effects on lakes (Tao et al., 2015), whereas its southern part belongs to the Tibetan Plateau (Fig. 1) where melting glacier and snows have enlarged lakes (Pekel et al., 2016). This unique geographical complexity has placed Xinjiang's lakes under strong yet contrasting impacts from both climate change and human interventions. The study of lake dynamics in Xinjiang will hence contributes to the understanding of lake changes in not only Northwest China but also the entire arid Central Asia. However, no collective analysis of the lake changes in Xinjiang has been conducted, although there have been a few studies for several individual lakes (Dilinuer and Aikebaer, 2010; Zhu et al., 2015). Using Landsat satellite remote sensing images collected between the late 1980s and 2015, this study aims at quantifying the changes in all lakes larger than 1 km^2 in Xinjiang and understanding the natural and human factors that cause the lake changes.

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https://doi.org/10.1016/j.jaridenv.2018.03.008
Received 14 June 2017; Received in revised form 6 January 2018; Accepted 20 March 2018
Available online 30 March 2018
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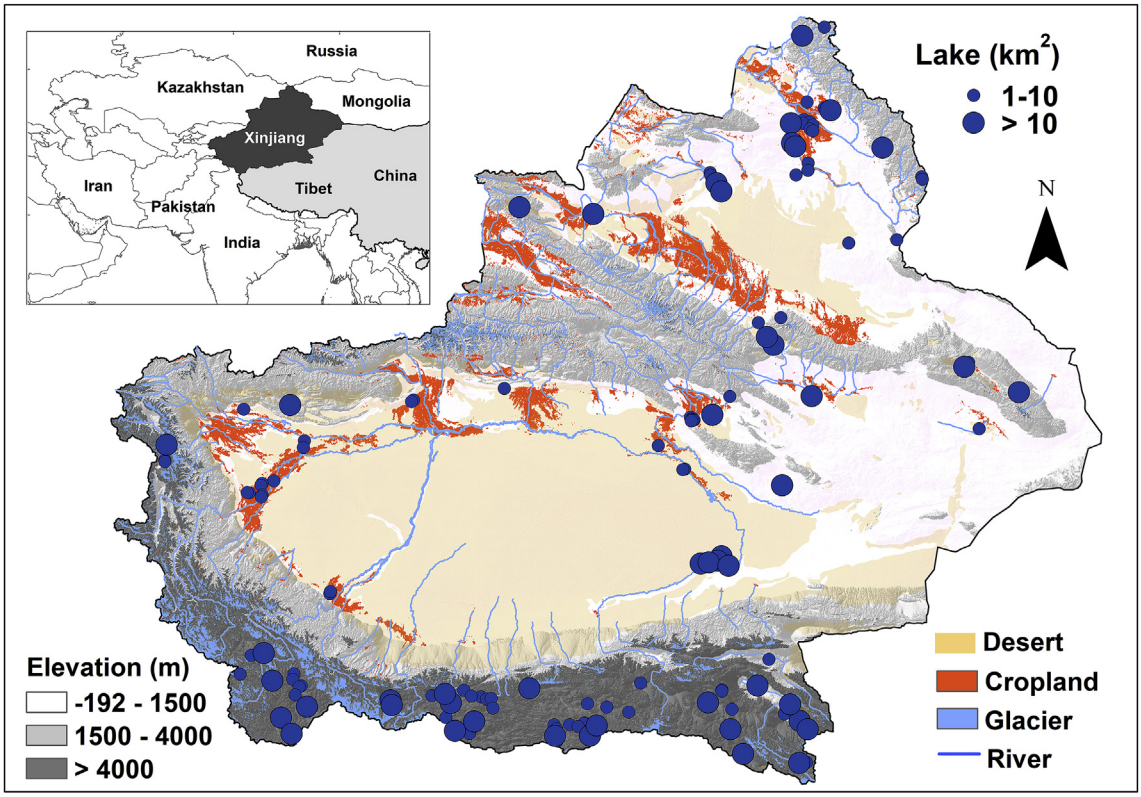

Fig. 1. Distribution of lakes in Xinjiang in background of topography and landcover. Most of the lakes in Xinjiang are distributed either on mountains covered by snow and glaciers or at the termini of rivers that are fed by meltwater from snow and glaciers.

2. Materials and methods

2.1. Landsat images and processing

We downloaded more than 1000 Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) remote sensing images from the USGS website (http://glovis.usgs.gov/) to establish the lake database for our study area. The quality of the selected images was carefully examined to ensure a cloud cover of less than 10%. In instances where the lake boundaries were sufficiently clear, a slightly higher degree of cloud cover was accepted. Because we were interested in the inter-annual trends of lakes, and because the seasonal changes did not impact the inter-annual trends (Fig. S1), we selected Landsat images in each summer (June to September, with only a few collected in May or October) between the late 1980s and 2015.

We used the Normalized Difference Water Index (NDWI) method to estimate the number and area of the lakes from the Landsat images. The NDWI is a classical method used to identify water bodies from remotely sensed images, and the overall accuracy of this method can be as high as 99.8% (McFeeters, 1996; Xu, 2006). The formula for calculating lake numbers and area is shown in Eq. (1):

$$NDWI = \frac{b_{\text{green}} - b_{\text{midinfrared}}}{b_{\text{green}} + b_{\text{midinfrared}}} \quad (1)$$

where b_{green} indicates the reflectance in the green band and $b_{\text{midinfrared}}$ indicates the reflectance in the mid-infrared band.

For the TM and ETM images, bands 2 and 5 were selected for calculating the NDWI (Xu, 2006; Tao et al., 2015). For the OLI data, the corresponding bands were 3 and 6 based on previous research (e.g., Li et al., 2014a). The calculation of NDWI was carried out in ArcGIS (version 10.1, ESRI®) with default setting. All the water bodies were extracted using the NDWI method and then visually inspected to exclude artificial ponds, rivers and reservoirs. We also referred to historical google earth images and published literature to determine the boundaries of some saline lakes.

2.2. Data on climate and human activities

Xinjiang has experienced significant climate changes in the past decades (Zhao et al., 2011). The land use patterns in Xinjiang have also been altered, including a dramatic increase in croplands (National Bureau of Statistics PRC, 2016). To explore the impacts of climate change and human activities on lake changes, we examined several possible factors that might induce lake changes, including annual mean temperature (MAT), annual precipitation (AP), Thornthwaite's moisture index (I_m) and the intensity of irrigation. The impacts of MAT on lakes are complex in Xinjiang: it causes not only a decrease in lake area through evaporation but also induces an increase in lake area by melting glaciers and snow (Cheng et al., 2002; Lan et al., 2007; Li et al., 2010). AP was chosen as it is one of the most important water supply to lakes. I_m indicates the combined effects of potential evapotranspiration and supply of water on lake changes, which was calculated using Eq. (2) (Thornthwaite, 1948; Thornthwaite and Mather, 1955; Fang and Yoda, 1990):

$$I_m = (100 * S - 100 * D) / PE \quad (2)$$

Where S is the water surplus, D is the water deficiency, and PE is the Thornthwaite potential evapotranspiration. The I_m value increases towards wetter climate condition. Irrigation also has a direct impact on lakes and it diverts meltwater from glaciers and snow to croplands.

MAT and AP were derived from CHELSA (Climatologies at high resolution for the earth's land surface areas) climate data set (http://chelsa-climate.org/). The CHELSA-based temperature is statistically downscaled from atmospheric temperatures and its precipitation incorporates orographic predictors (Karger et al., 2017). These make

CHELSA very suitable for use in mountainous regions like Xinjiang. I_m was calculated from CHELSA data using the Thornthwaite equation (i.e., Eq. (2)). The area of irrigated croplands was obtained from a census report of Xinjiang (Xinjiang Bureau of Statistics, 1989–2015).

2.3. Data analysis

We first identified all lakes larger than 1 km^2 in Xinjiang in the late 1980s and 2015, and quantified their changes in lake area and number of lakes during this period. To better illustrate the changes in lakes, we divided the lakes into three size classes: small lakes with area between 1 and 10 km^2; medium lakes with area between 10 and 50 km^2; and large lakes with area greater than 50 km^2 (Tao et al., 2015).

Because the medium and large lakes comprise most of the lake area, we further examined their temporal changes and the associated driving forces since the late 1980s. To that end, their relative water area (RWA) was calculated for each of the following nine periods: 1985–1990, 1991–1993, 1994–1997, 1998–2000, 2001–2003, 2004–2007, 2008–2010, 2011–2013, and 2014–2015. The RWA was calculated using Eq. (3) (Fang et al., 2006; Tao et al., 2015):

$$RWA(\%) = \frac{1}{n}\sum_{i=1}^{n}(A_i/A_i^s) \times 100 \quad (3)$$

where n, A_i and A_i^s represent the number of the medium and large lakes, the area of the i_{th} lake, and the area of the i_{th} lake in the base period, respectively. The base period in this study was set as 1991–1993 because Landsat images were available during this period for all the medium and large lakes.

To analyze the impacts of irrigation on lake change, we further classified the medium and large lakes into two groups according to the land use map of Xinjiang (Glob Cover 2009, http://due.esrin.esa.int/page_globcover.php): lakes within a 5-km buffer of croplands and those that were not within this buffer (Fig. 2a). A buffer of 10 km was also used for the division of lake groups and the same results were observed, so we only reported the results using the 5-km buffer. As shown in Figs. 1 and 2 and Fig. S2, irrigation-affected lakes were mainly distributed in the densely populated areas, and those not affected by irrigation were in the less populated glacier regions boarding with the Tibetan Plateau. Thus, we hereafter referred the first lake group to as cropland lake region and the second as glacier lake region.

Lastly, RWAs were calculated for all the medium and large lakes in Xinjiang, those in its cropland lake region and in its glacier lake region, respectively. The contribution of each of the abovementioned climatic and human factors to the changes in RWAs was assessed using General Linear Models (GLMs), as implemented in the statistical package R, version 3.0.3 (R Development Core Team, 2014). Since CHLSA data are currently only available from 1979 to 2013, we used one-year lagged CHELSA climate to match with the time series of RWAs.

Table 1
Changes in area and number of lakes in Xinjiang between the late 1980s and 2015.

Item	Lake size class (km^2)			All lakes
	1–10	10–50	> 50	
Number of lakes in the late 1980s	78	25	18	121
Total area of lakes in the late 1980s (km^2)	238.3	344.1	4912.3	5494.7
Number of lakes in 2015	91	26	18	135
Total area of lakes in 2015 (km^2)	314.5	517.4	5613.4	6445.2
Number of dried-up lakes	6	3	0	9
Number of new lakes	19	4	0	23
Change in number of lakes	13	1	0	14
Percentage of change in number of lakes (%)	16.7	4	0	11.6
Change in lake area (km^2)	76.1	173.3	701	950.5
Percentage of lake area change (%)	32.0	50.4	14.3	17.3

3. Results

3.1. Changes in lakes between the late 1980s and 2015

In the late 1980s, there were 121 lakes with area > 1 km^2 in Xinjiang, which occurred at an elevation of 194 m–4982 m above sea level (Fig. 1). These lakes had a total area of 5495 km^2. Of the total lakes, 43 (35.5%) were medium or large lakes (> 10 km^2) and together had a total area of 5256 km^2 which accounted for 95.7% of the total lake area (Table 1, Fig. 3). Over the past 30 years, the total area of Xinjiang's lakes increased from 5495 km^2 to 6445 km^2 with an increase of 950 km^2 (17.3%) (Table 1, Fig. 3). Increasing trends in lake area were notable in all sizes of lakes (Fig. 3a, Table 1). In terms of the changes in lake numbers, nine lakes dried up and 23 newly formed. Considering only medium and large lakes, three lakes dried up and four newly formed (Table 1). Similar to the changes in lake area, the number of lakes either increased or remained the same across all lake sizes.

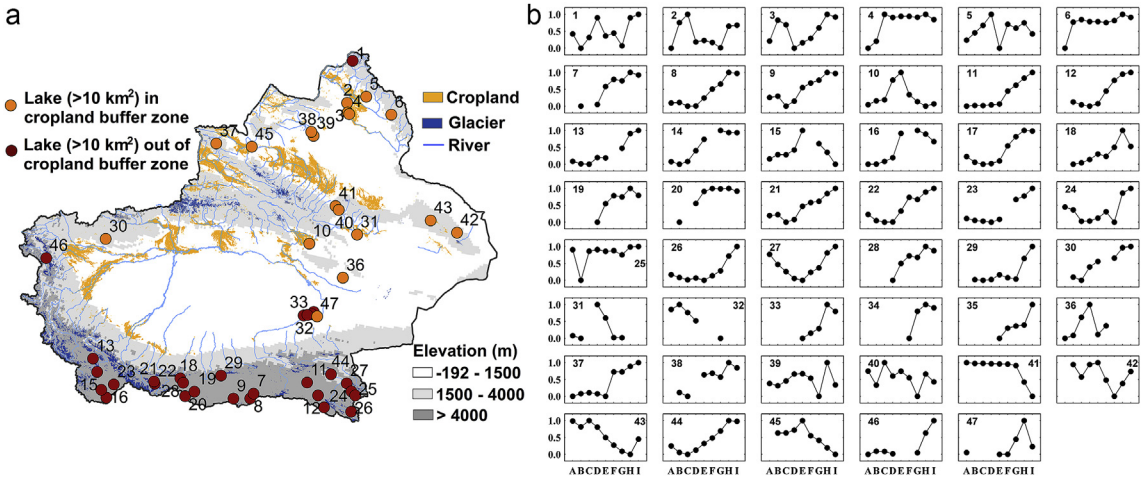

Fig. 2. Distributions of the 47 medium- and large-sized lakes, croplands, rivers and glaciers in Xinjiang (a) and the temporal changes of the medium- and large-sized lakes (b). Area of the lakes has been normalized to show only the temporal change patterns. The R^2, p-value and slope for the temporal changes of lake area for each lake are listed in Table S1. The characters A, B, C, D, E, F, G, H, and I on the x-axis represent the nine periods: 1985–1990, 1991–1993, 1994–1997, 1998–2000, 2001–2003, 2004–2007, 2008–2010, 2011–2013, and 2014–2015, respectively.

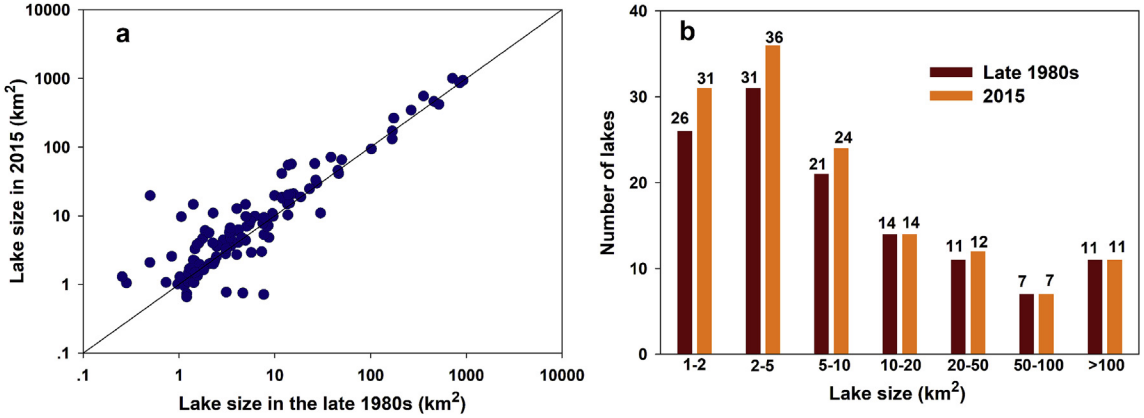

Fig. 3. Changes in lakes in Xinjiang between the late 1980s and 2015. (a) Scatter plot showing general trends of the changes in lake size (on logarithmic scale); the points (lakes) above the 1:1 line indicate an increase in size of the lake while those below the line show a drop of lake size. (b) The frequency distribution of lake numbers in the late 1980s and 2015.

3.2. Temporal changes in medium and large lakes

29 (87.9%) of the 47 medium and large lakes increased significantly ($p < 0.05$) in area over time, and most of these lakes were in the glacier lake region (Fig. 2, Table S1). Some lakes showed significant reductions in water area, especially after the year 2000, and most of these lakes were in the cropland lake region (Fig. 2, Table S1). The temporal changes in lake area of all the 47 medium and large lakes, as indicated by RWAs, exhibited an increasing trend during the past 30 years (Fig. 4a): it increased substantially in the 1990s, was relatively stable in the 2000s, and finally began to increase again (since 2010).

However, when examined at regional scales, we found that the temporal changes in lake area in the cropland lake region and those in glacier lake region were substantially different. The area (RWA) of irrigation-affected lakes increased prior to 1998–2000 but since then declined dramatically (Fig. 4b). In contrast, the RWA values of lakes without irrigation activities exhibited a persistent increase over the past 30 years (Fig. 4c). Thus, the increasing trend in lake area in Xinjiang was mainly driven by the increase in lake area in the less populated glacier lake region, whereas the cropland lake region has been suffering from rapid lake shrinkage.

3.3. Effects of climate changes and human activity on lake changes

During the past 30 + years, temperature increased in both the cropland lake region and the glacier lake region (Fig. 5). Precipitation and I_m increased in the glacier lake region but stayed relatively stable in the cropland lake region (Fig. 5). It is worth noting that the intensity of irrigation in the cropland lake region has drastically increased, especially since the year of 2000. GLM regression suggested that MAT, AP and irrigation were the dominant drivers of lake changes at the Xinjiang level (Table 2). Further regional GLM analyses revealed that MAT and AP were responsible for the increase of lakes in the glacier lake region, explaining 60.9% ($p < 0.05$) and 33.4% ($p < 0.05$) of the variance in lake area, respectively (Table 2). However, in the cropland lake region, none of the climatic factors explained the lake variances significantly and only irrigation showed considerable control on lake changes (29.4%, $p < 0.05$).

4. Discussion

Our quantitative analysis indicated large regional differences in lake changes and the associated driving forces in Xinjiang in the past decades. In the glacier lake region, lake changes were driven by both climate warming and increases of precipitation. The climate in the glacier region was changing towards wetter conditions as evidenced by the increase of precipitation, I_m and, especially, rising temperature. Rising temperature in Xinjiang can increase lake area by melting large amounts of snow and glacier ice. Seen in Figs. 1 and 2a, most of Xinjiang's rivers originate in the mountains and are supplied by meltwater from ice and snow. These rivers flow down to the basin areas and finally into terminal lakes. The role of glacier as a reliable water supply for downstream environment and population in Xinjiang has been well recognized (Pritchard, 2017). Specifically, the Altai Mountains in northern Xinjiang provide water to both Xinjiang and western Mongolia (Batnasan, 2003). The Mt. Tianshan, located in central Xinjiang, provides water for inland areas (Lan et al., 2007; Pritchard, 2017), and the Kunlun Mountains in southern Xinjiang, along the border with the Tibetan Plateau, also provide ample water for the nearby lakes (Li et al., 2010; Pritchard, 2017). Although we don't have direct measures of

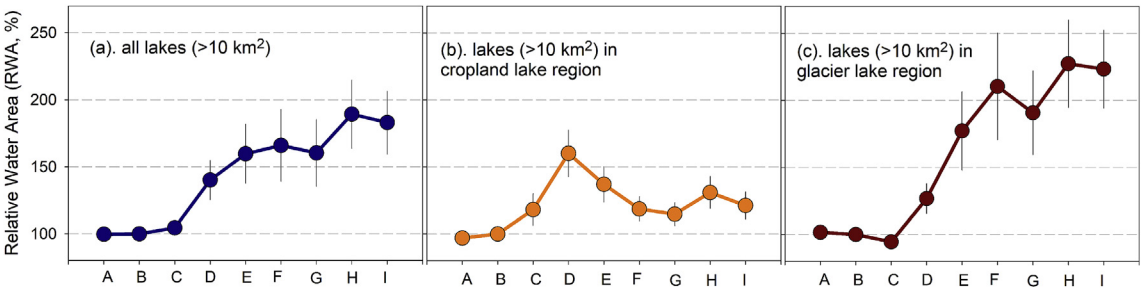
Relative Water Area (RWA, %)
250
200
150
100
(a). all lakes (>10 km²)
(b). lakes (>10 km²) in cropland lake region
(c). lakes (>10 km²) in glacier lake region
A B C D E F G H I

Fig. 4. Temporal changes of the medium- and large-sized lakes (> 10 km^2) in Xinjiang as indicated by relative water area (RWAs). (a) all the lakes (> 10 km^2) in Xinjiang; (b) lakes (> 10 km^2) in the cropland lake region; and (c) lakes (> 10 km^2) in the glacier lake region. The characters A, B, C, D, E, F, G, H, and I on the x-axis represent the nine periods: 1985–1990, 1991–1993, 1994–1997, 1998–2000, 2001–2003, 2004–2007, 2008–2010, 2011–2013, and 2014–2015, respectively. Error bar indicates the standard error of lake area.

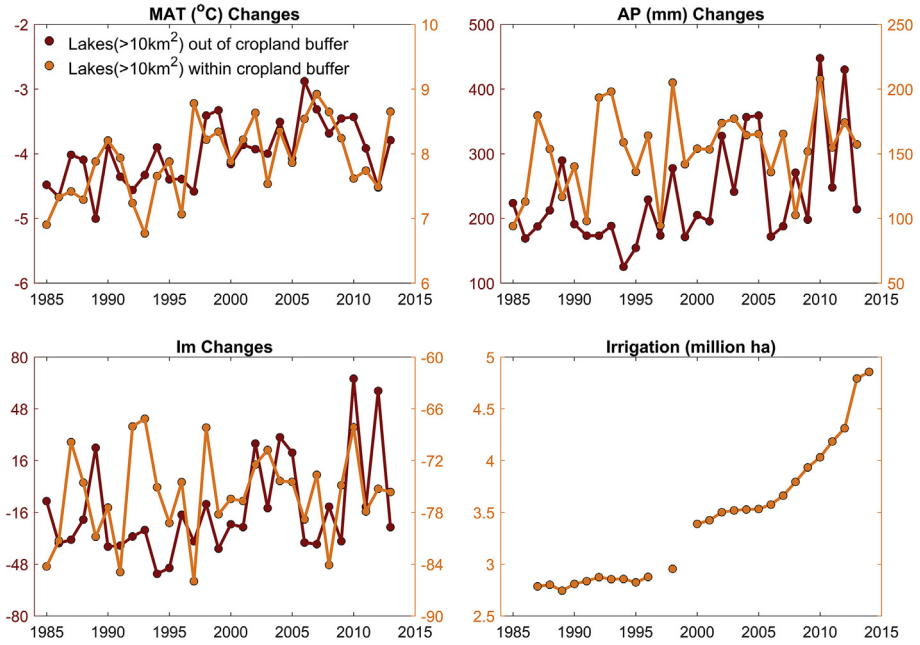

Fig. 5. Temporal changes in the influencing factors of lake changes in cropland and non-cropland (glacier) lake regions in Xinjiang.

Table 2
Effects of climate change and irrigation on changes in lakes in Xinjiang, using multiple GLM regression.

Variable	Entire Xinjiang		Glacier lake region		Cropland lake region	
	MS	SS, %	MS	SS, %	MS	SS, %
MAT	4899.4	49.5**	12,666.5*	60.9*	592.8	22.3
AP	4177.1	42.2**	6936.8*	33.4*	611.9	22.9
I_m	0.1	0	176.2	0.8	579.8	21.8
Irrigation	765.6	7.8*	/	/	782.6*	29.4*
Residuals	49	0	989	4.8	95.4	3.6

MS stands for mean squares; SS stands for the proportion of the variance explained by the variable. *$P < 0.05$. **$P < 0.01$.

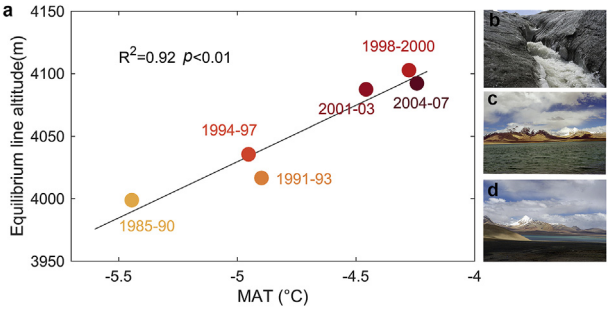

Fig. 6. Relationship between MAT and estimated average equilibrium line altitude (an indicator of melting glacier volume) of the melting Glacier No.1 at Tianshan Mountains in central Xinjiang from 1987 to 2007 (a). The equilibrium line altitude data were taken from Dong et al. (2012). The photos on the right show the melting glacier and snow water of at Tianshan Mountains (b, photo courtesy of Xinhua news), and the glacier and lakes at Kunlun Mountains in south Xinjiang (c and d, photos were taken during our field survey in Xijiang).

meltwater produced from glaciers and snow, previous studies have shown that there is a close relationship between glacier meltwater flux and air temperature (Cheng et al., 2002; Lan et al., 2007; Li et al., 2010; Dong et al., 2012) (Fig. 6). In the last 30 years, the annual mean temperature in Xinjiang has significantly increased, with an increasing rate of up to 0.4 °C/10 years, which have resulted in a large supply of meltwater to the lakes (Wang et al., 2013).

It was a different story in the cropland lake region. Although climate changes explained some variances in lake changes (22.3% by warming temperature and 22.9% by precipitation), the explaining powers were lower and insignificantly compared with that of irrigation (Table 2). The intensity of irrigation increased largely since around the year of 2000 (Fig. 5), which was well coincident with a significant decline in lake area (Fig. 4b). In fact, a large area of Xinjiang's natural lowlands has been reclaimed to croplands over the past decades, and consequently the area of irrigated lands has increased from 2.7 million hectares in 1985 to 4.8 million hectares in 2015 (Fig. 5, Fig. S3). Some of the lakes have even been artificially transformed into reservoirs for the use of irrigation. We argue that high-intensity irrigation since 2000 may have overconsumed the meltwater from glacier and snow, causing large reductions of lake area. Several previous studies support this viewpoint. For instance, although the upper reach of Tarim river has gained runoff because of increasing meltwater from the mountainous region, its lower reach has been suffering from persistent drought as a direct result of agricultural irrigation (Zhang et al., 2003; Xu et al., 2010; Thevs et al., 2015). In Manas Lake Basin, 15 reservoirs and 1221 mechanical and electrical wells have been constructed along the Manas River for irrigation during the past years (Yao et al., 2007). It has been estimated that the amount of extracted water may even exceed the total runoff of the River, which led little river runoff to flow to Manas Lake. Similarly, 10 reservoirs have been built in the Aibi Lake Basin during the past few decades (Li et al., 2014b). The amount of water diverted from local rivers is so large that water no longer flows into Aibi Lake. The same situation has occurred in other lake basins, such as the Yanqi Basin and the Bosten Lake Basin, where the volume of diverted water for irrigation increased from 3×10^8 m^3 in 1950 to 10.13×10^8 m^3 in 2012, resulting in a significant reduction in the water volume of Bosten Lake (Ilnur et al., 2015).

In addition to the climatic factors and irrigation activities mentioned above, some individual lakes in Xinjiang have been influenced by other human activities, such as government protection policies. For instance, the area of Wulunguhu Lake, Jili Lake, Tangba Lake, Ailike Lake, and Tuolekule Lake (Lake IDs 2, 3, 5, 39 and 42 in Fig. 2, respectively) increased after an initial decline because of anthropogenic management or interventions. Taking Ailike Lake as an example, the construction of the Baiyanghe Reservoir and the Huangyangquan

Reservoir in the 1980s has led to the drying up of this lake, but in August 2000, local government launched a water diversion project to restore Ailike Lake (Li et al., 2008). For this reason, Ailike Lake now maintains a relatively stable area and water level, although the area of irrigated croplands in this region is still increasing.

5. Conclusion and implications

During the past 30 years, owing to melt of glaciers and increase of precipitation, lake area in the mountainous region in Xinjiang has increased continuously. In contrast, lakes in the cropland region increased before 2000 and then decreased rapidly, mainly because of the irrigation activities.

Changes of lakes in Xinjiang can also be seen in other parts of the arid Central Asia (Bai et al., 2011; Micklin, 2007). The results of this study therefore not only suggest an ongoing water crisis in Northwest China but also help understand the lake dynamics in the entire arid Central Asia. Irrigation agriculture has been important in the dry-lands of Central Asia to satisfy the growing demand for food (O'Hara, 1997; Lioubimtseva and Henebry, 2009), which has caused negative effects on local environment (Lioubimtseva et al., 2005). The Aral Sea's eastern basin even dried up as a direct result of intensive irrigation (Micklin, 1988, 2007). Although recent studies suggested that the melting glaciers can provide large amount of water for this critical region (Pritchard, 2017), our results provided ample evidence that the benefits of glacier melt can be substantially offset by high intensity of irrigation. We thus call an urgent need for a policy of lake management and sustainable water utilization in the entire arid region of Central Asia. The management of limited water resources should be strengthened, and cropland irrigation should be scientifically sound, to achieve the coordinated and sustainable development of both environment and socioeconomy.

Acknowledgements

This work was funded by National Natural Science Foundation of China (31621091, 31330012 and 41625003).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jaridenv.2018.03.008.

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